Simulation of Inverse Piezoelectric effect in degradation AlGaN/GaN devices

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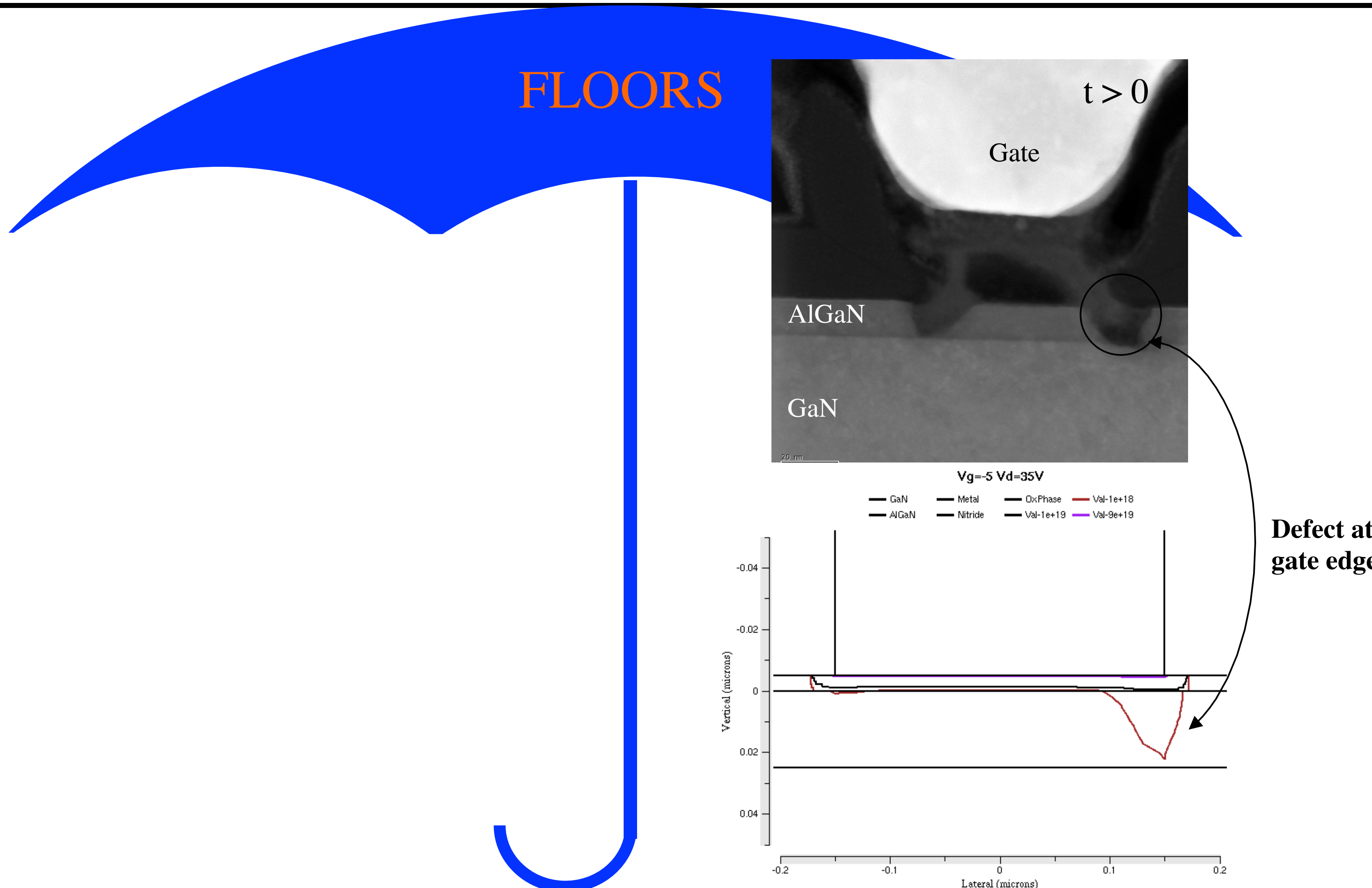
Simulation Approach



t=0, As Built

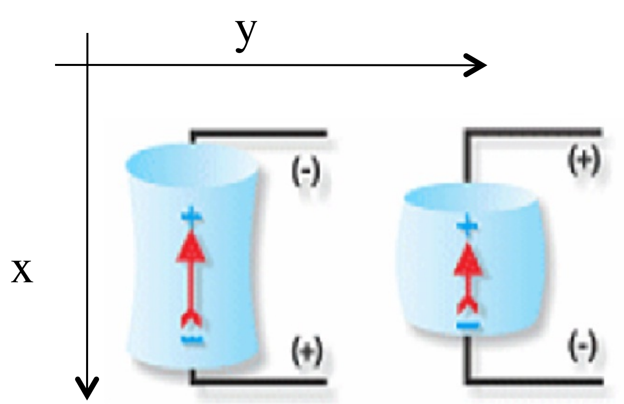
t>0, Degradation

1] Park S.Y, Kim, M.J et al Microelectronics Reliability 49 2009 pp:478– 483

Strain from Inverse Piezoelectric effect

1) Relationship (reduced to linear) between electric field, E and mechanical strain, ε: $\boldsymbol{\varepsilon_i = d_{ij} E_j}$ where j=1…3 and i=1….6

2) Assuming GaN crystal oriented such that polarization is vertical , $\varepsilon_{xx} = d_{33}E_x$, $\varepsilon_{yy} = d_{31}E_x$



Assuming constant d_{33}, d_{13}, d_{15} resultant strains given by:

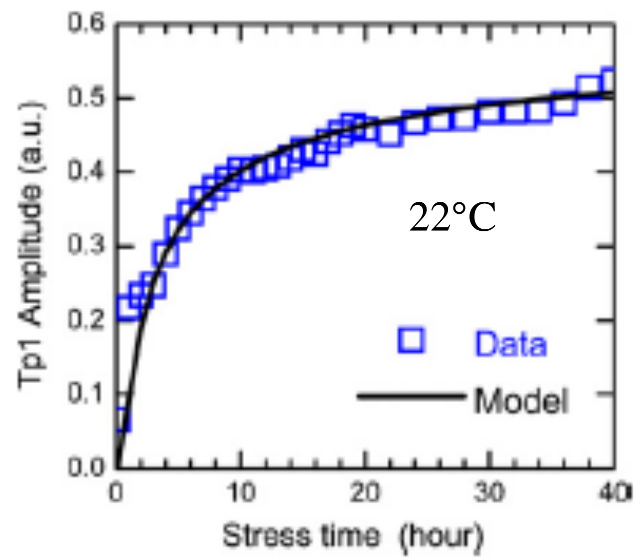
$$\begin{pmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{xy} \end{pmatrix} = \begin{pmatrix} d_{33} & 0 \\ d_{31} & 0 \\ 0 & d_{15} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

GaN: d_{33} =3.4pm/V , d_{31} =-1.7pm/V , d_{15} =3.1pm/V

Relating Strain to Impurity Diffusion

- Trap concentration increases over time and matched to an infinite source diffusion model:

$$Tp1(z,t) = Tp1_{surface\ \rho}\left[1 - erf\left(\frac{z}{2\sqrt{Dt}}\right)\right]$$



- Strain known to enhance diffusion:

$$D' = D * exp\left(\frac{Q's}{kT}\right)$$

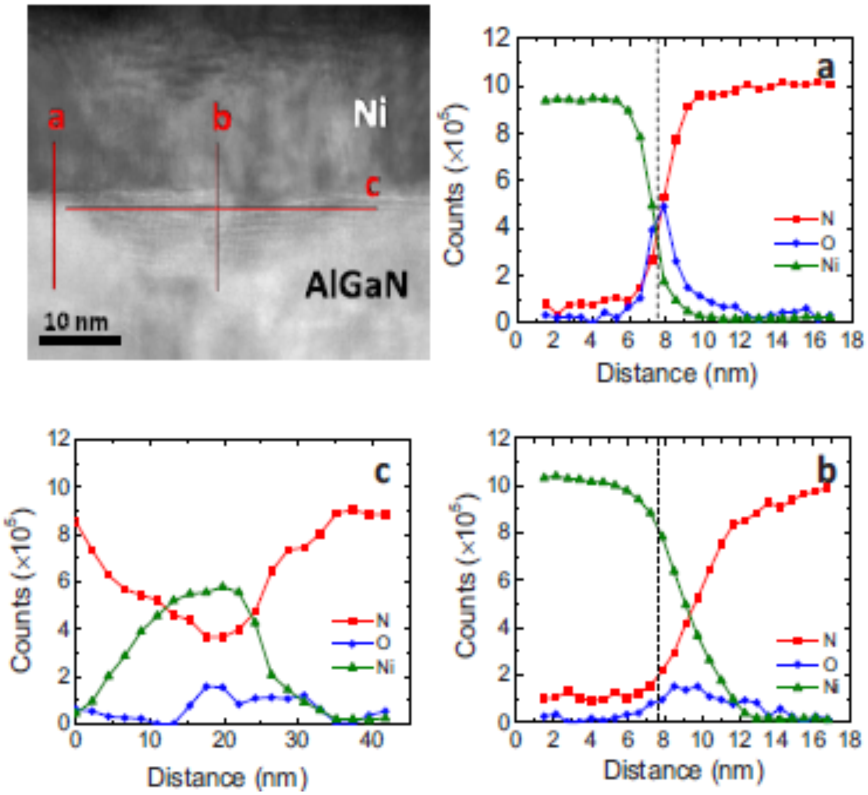
  - D' = Enhanced diffusivity due to strain
  - D = Diffusivity of Ni in AlGaN at given temp, T
  - Q' = Energy per unit strain
  - s = Total strain at point

2] Kuball, M et al Microelectronics Reliability 51 2011 pp:195– 200

3] Tapajna M, Mishra U.K., Kuball M. Applied Phys. Lett. Vol 97, No 023503, 2010

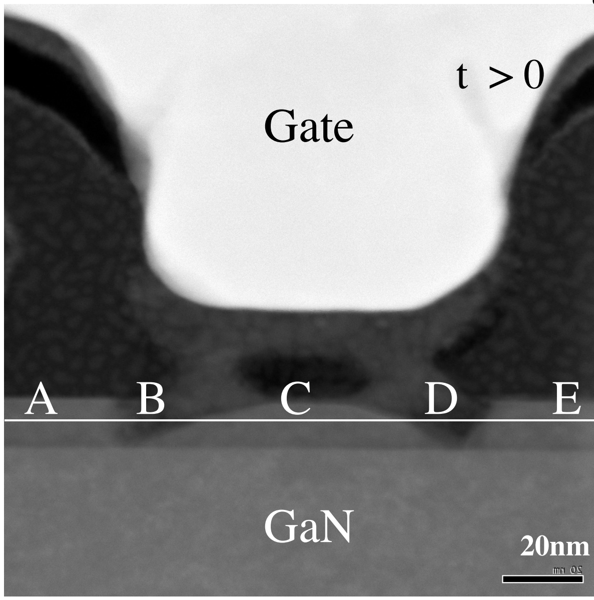
TEM images of impurity diffusion

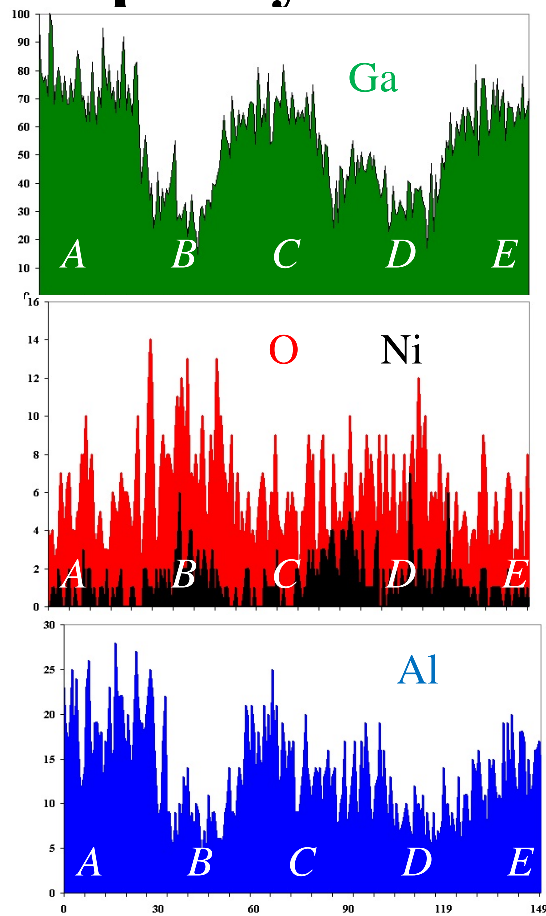
- Observed for Ni/Au gates commonly near edges
- Off-state, step-stressed
- EELS line scans show Ni ,O diffusion into AlGaN



4] Ren, F et al. JVST B 5 Microelectronics and Nanometer structures Apr 2011

TEM images of impurity diffusion



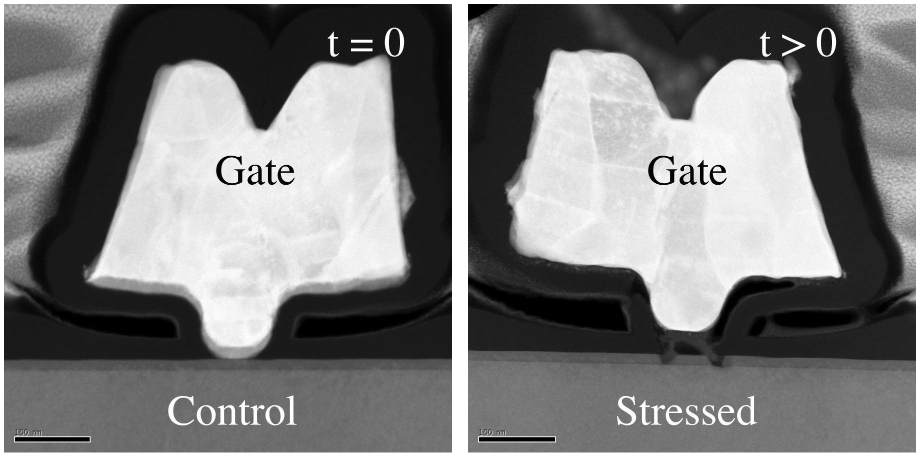


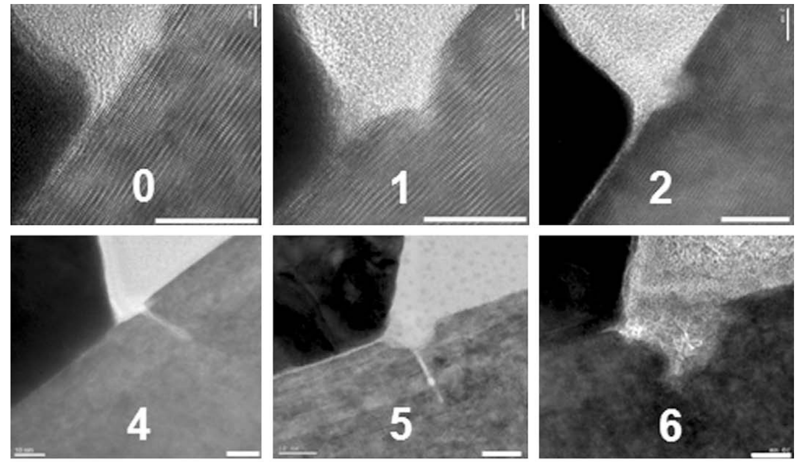
- **Ga decreases in the arch feet**
- **Ni and O increases in the arch feet**
- **Al decreases in the arch feet**

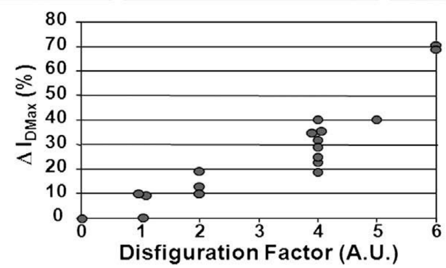
EDS line scans show Ni ,O diffusion into AlGaN

7] Holzworth, M. R, Rudawski, N.G, Pearton, S.J, Ren, F Applied Phys. Lett. Vol 98, No 122103, 2011

TEM images of degraded devices





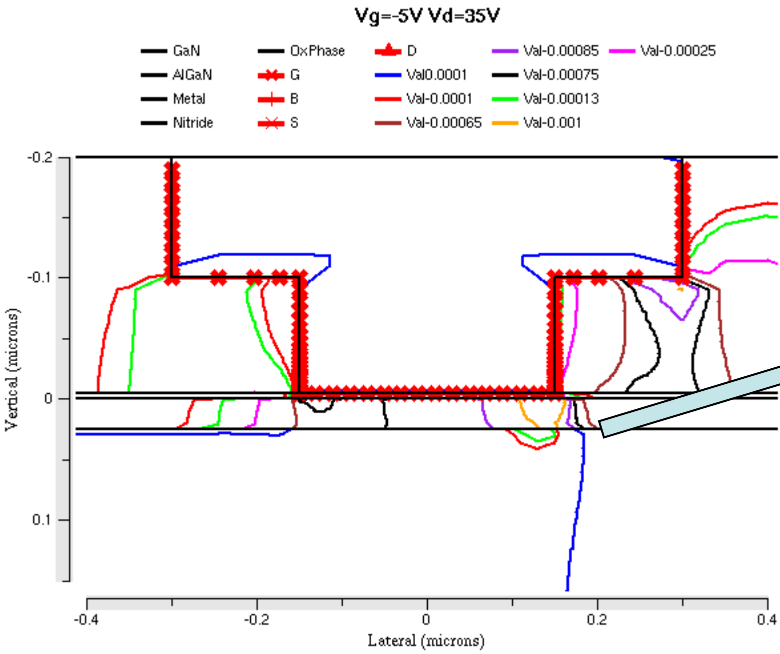


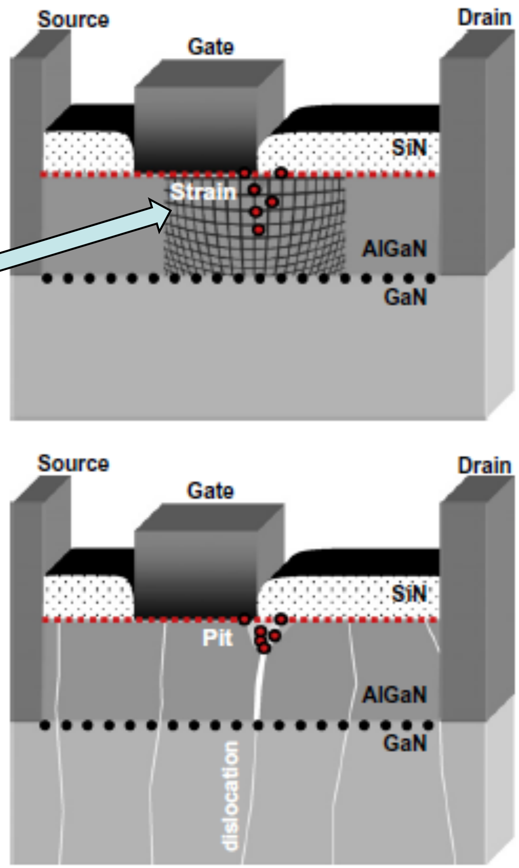
- Physical degradation related to I_D reduction
- $I_{D\,MAX}$ reduction as much as 70%
- Non-recoverable

7] Holzworth, M. R, Rudawski, N.G, Pearton, S.J, Ren, F Applied Phys. Lett. Vol 98, No 122103, 2011

1] Park S.Y, Kim, M.J et al Microelectronics Reliability 49 2009 pp:478– 483

Strain distribution in Off-State around T-gate





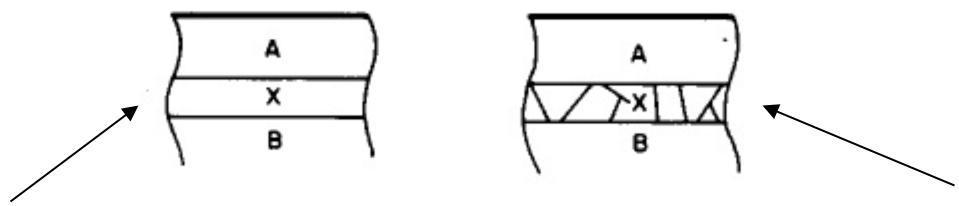
- Impurity diffusion driven by strain
- Pit formation suggests diffusion

2] Kuball, M et al Microelectronics Reliability 51 2011 pp:195– 200

New: Importance of interfacial layer

Diffusion barriers in thin films

- Diffusion barriers retard degradation by interposing a layer which suppresses, or at least strongly reduces undesirable transport of atoms
- Defects and grain boundaries are of primary significance for barriers
- The presence diffusion pipes, weak spots and other extended structural defects in the thin film could entirely negate its usefulness as a barrier



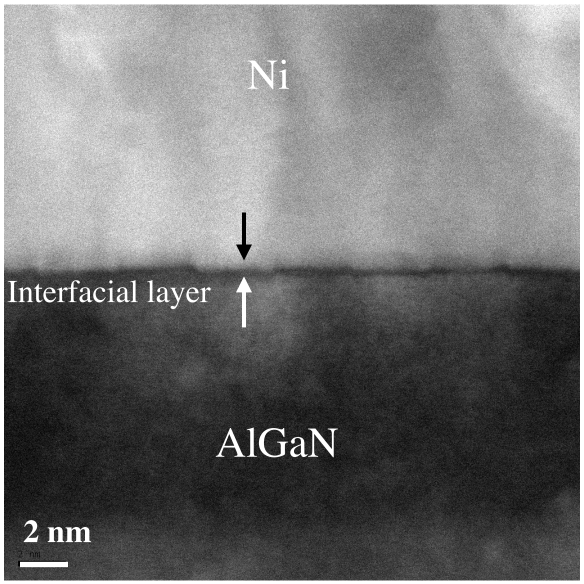
X as Passive Barrier

X as Non-Barrier

6] Nicolet, M. A Thin Solid Films, Volume 52, 1978 pp:415– 443

New: Importance of interfacial layer

Diffusion barriers in thin films



- Inclusion of thin oxide layer in simulation as a diffusion barrier
- Initially assuming

$$Oxide_{diffusivity} = \frac{AlGaN_{diffusivity}}{10}$$

where $AlGaN_{diffusivity} = 3.5e17 cm^2 / s$

- Interfacial layer is ~5Å
- Composed of NiOx and AlOx (LEAP)
- $a_{NiO} = 4.176 \overset{o}{A}$ vs $a_{GaN} = 3.189 \overset{o}{A}$. Compressive layer
- Grain size unknown

7] Holzworth, M. R, Rudawski, N.G, Pearton, S.J, Ren, F Applied Phys. Lett. Vol 98, No 122103, 2011

Simulation Flowchart

Strain distribution within structure determined as a function of bias → $\begin{pmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{xy} \end{pmatrix} = \begin{pmatrix} d_{33} & 0 \\ d_{31} & 0 \\ 0 & d_{15} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$

⇓

Diffusion of metal impurity driven by strain → $D' = D * exp\left(\frac{Q's}{kT}\right)$

⇓

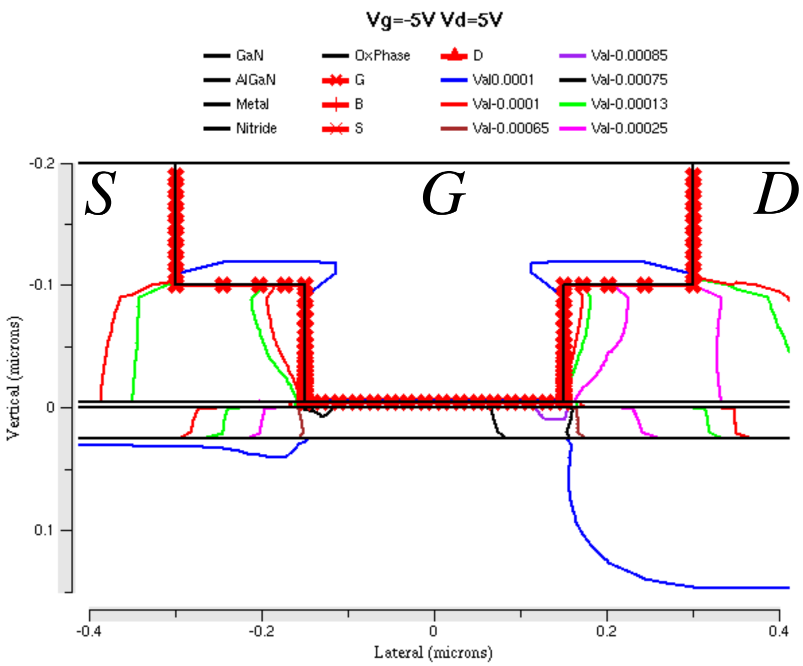
Metal impurity profile fed into Poisson's equation → $\frac{d^2\varphi(x)}{dx^2} = -\frac{\rho(x) + Impurity(x)}{\epsilon}$

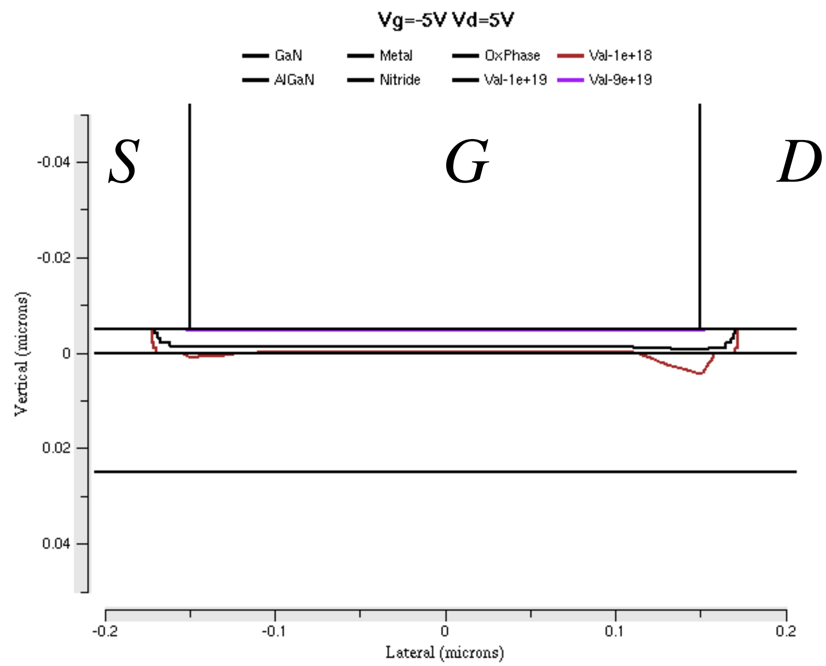
⇓

IV curves determined for each impurity profile → $\frac{d(Elec)}{dt} = n * \mu_n * \frac{d^2\emptyset(x)}{dx^2}$

Strain↕dir & Impurity diffusion

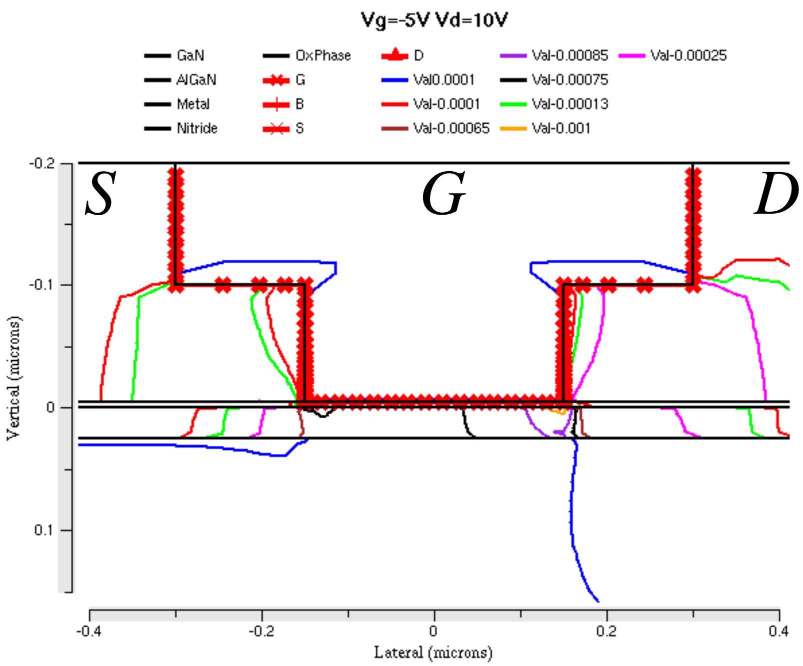
Vg=-5V Vd=05V

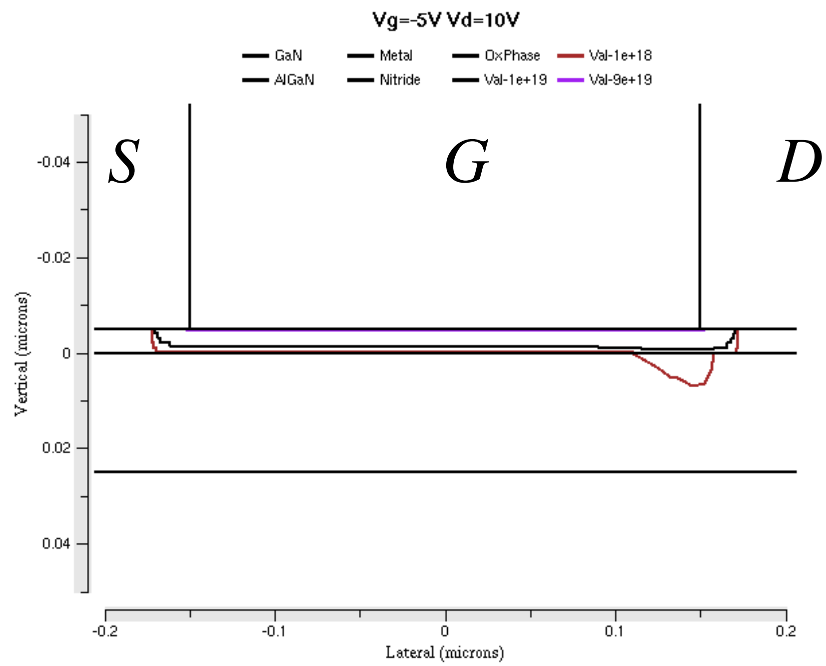




Strain↕dir & Impurity diffusion

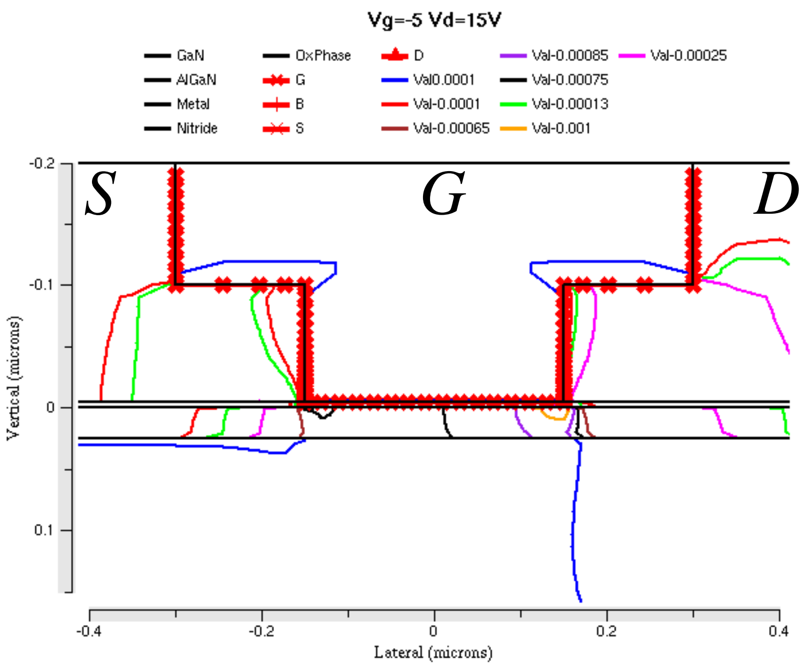
Vg=-5V Vd=10V

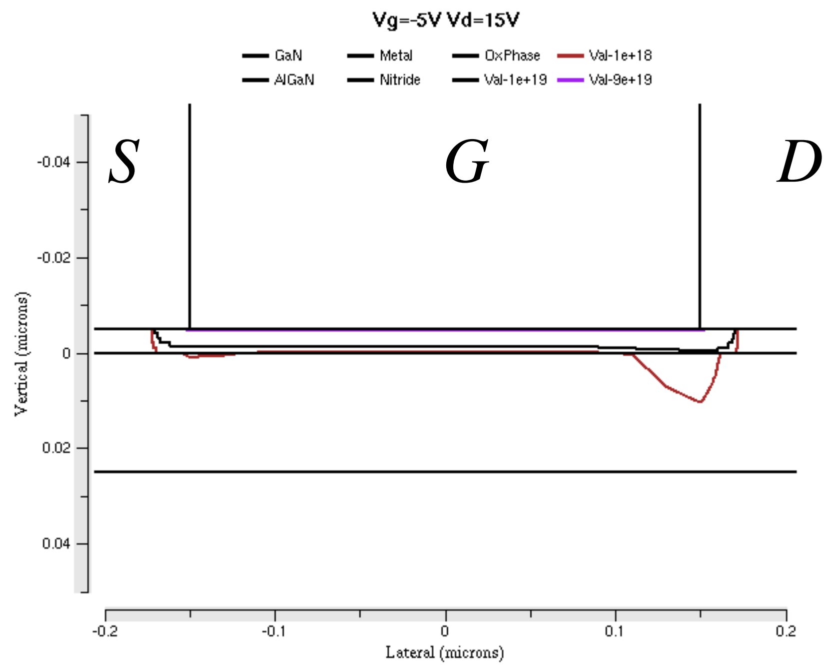




Strain↕dir & Impurity diffusion

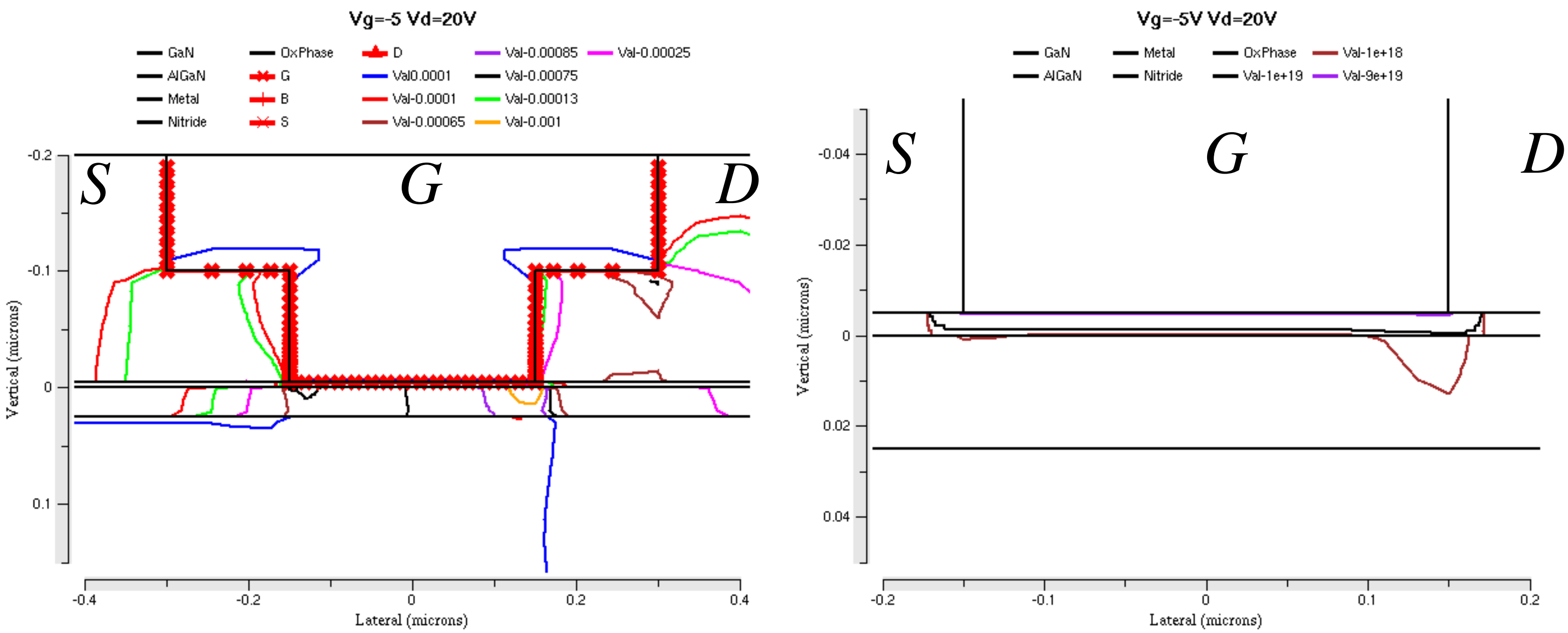
Vg=-5V Vd=15V



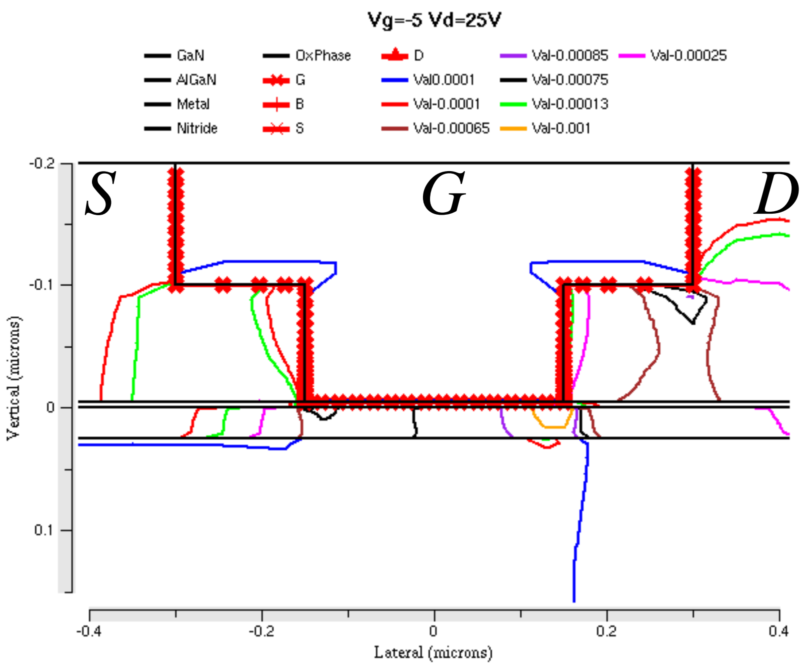


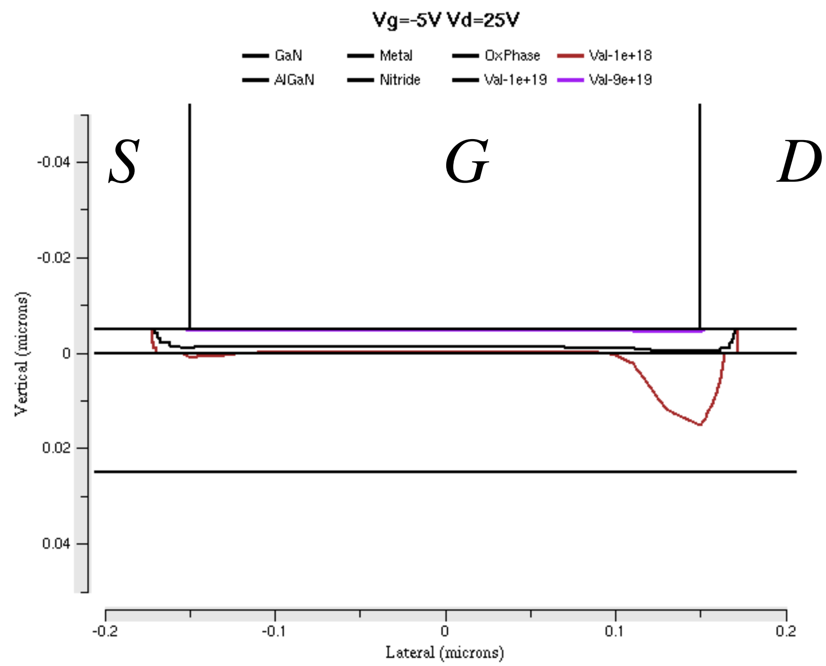
Strain↕dir & Impurity diffusion

Vg=-5V Vd=20V



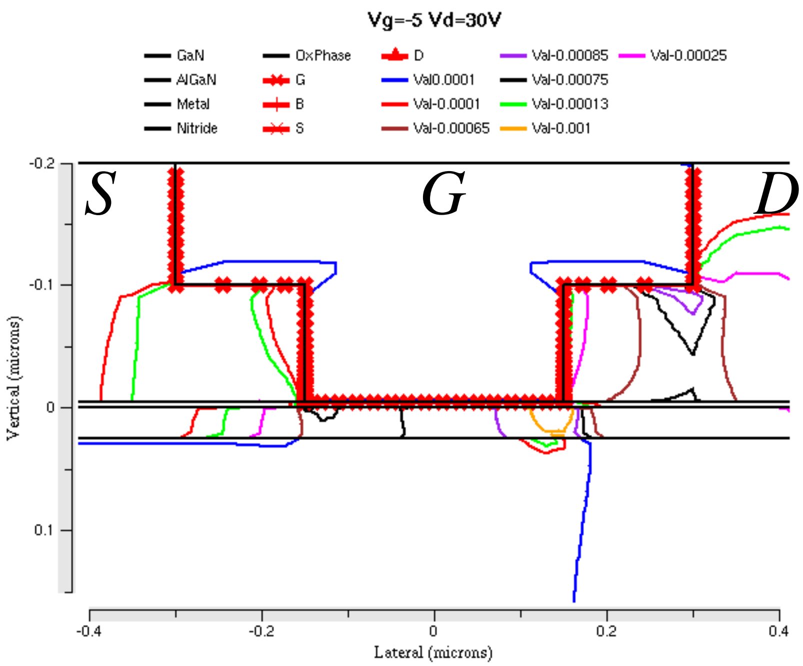
Strain ↕ dir & Impurity diffusion
Vg=-5V Vd=25V

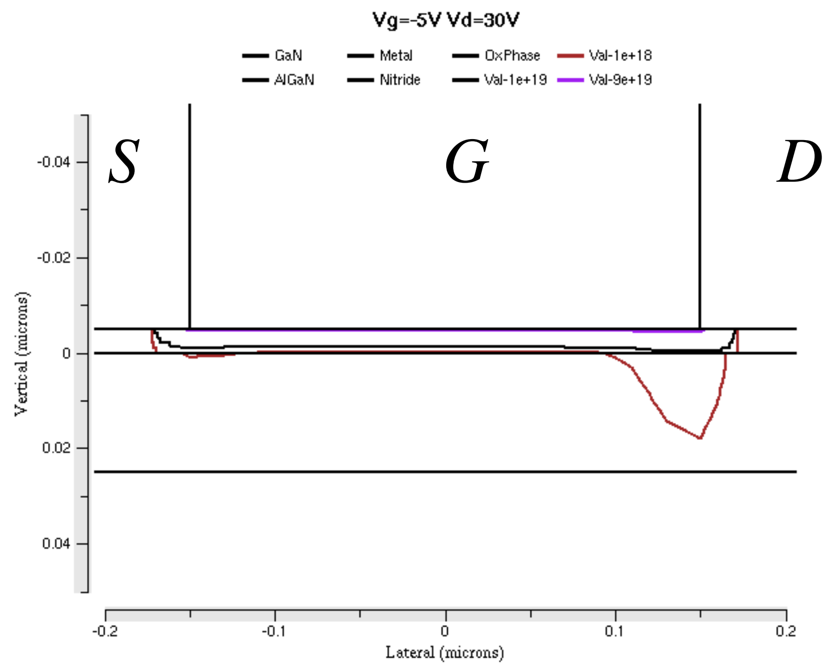




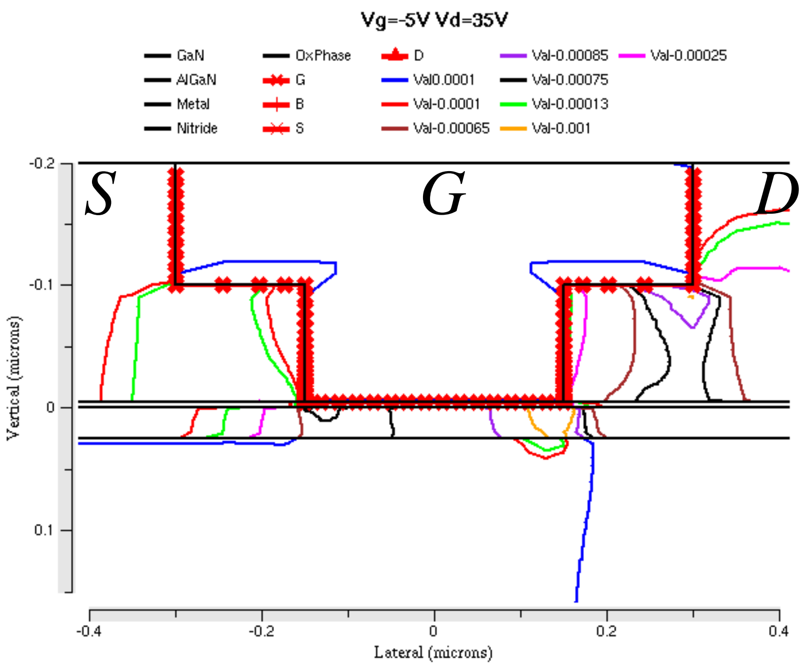
Strain ↕ dir & Impurity diffusion

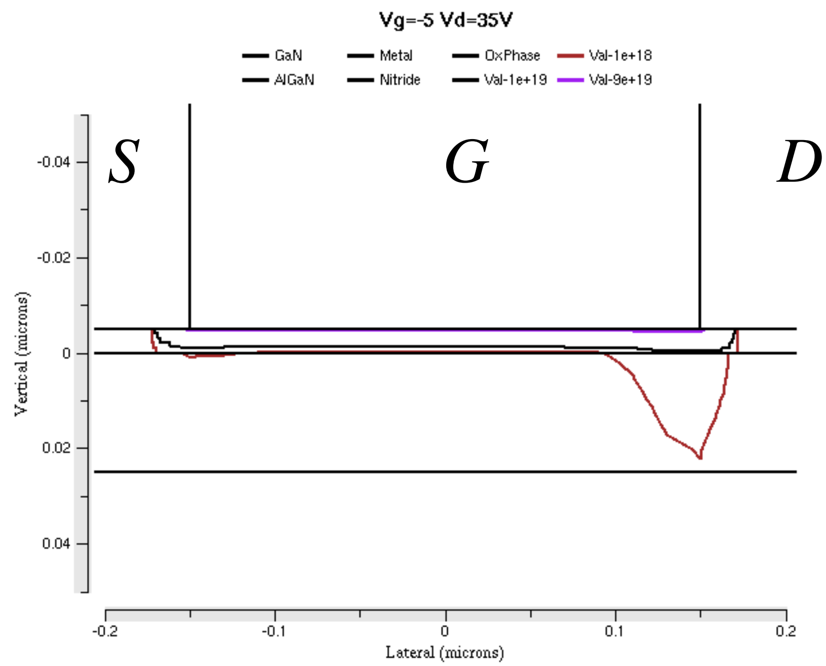
Vg=-5V Vd=30V



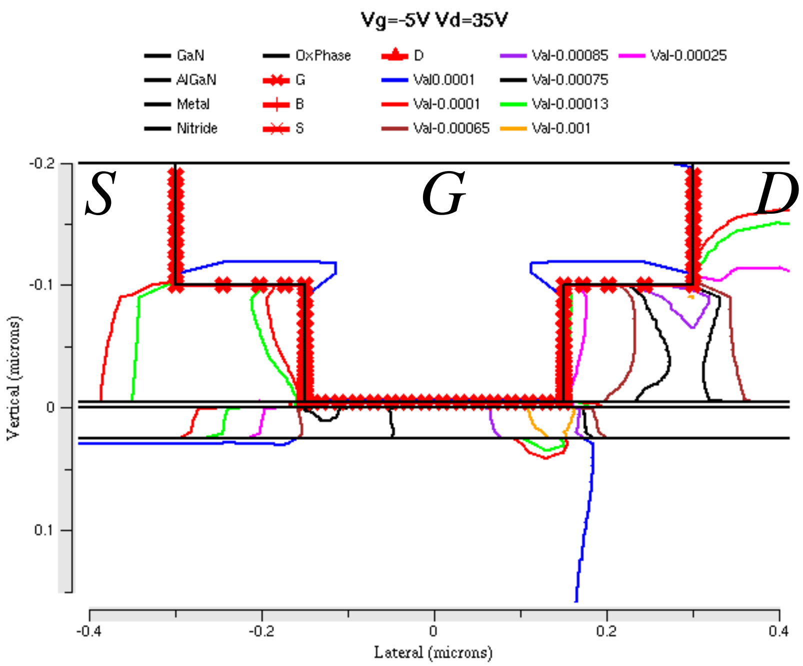


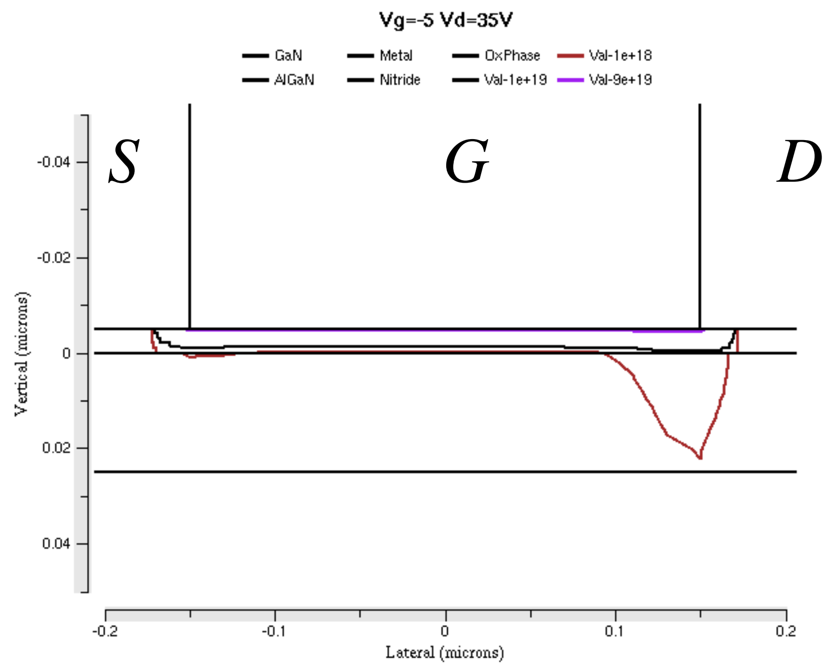
Strain ↕ dir & Impurity diffusion
Vg=-5V Vd=35V





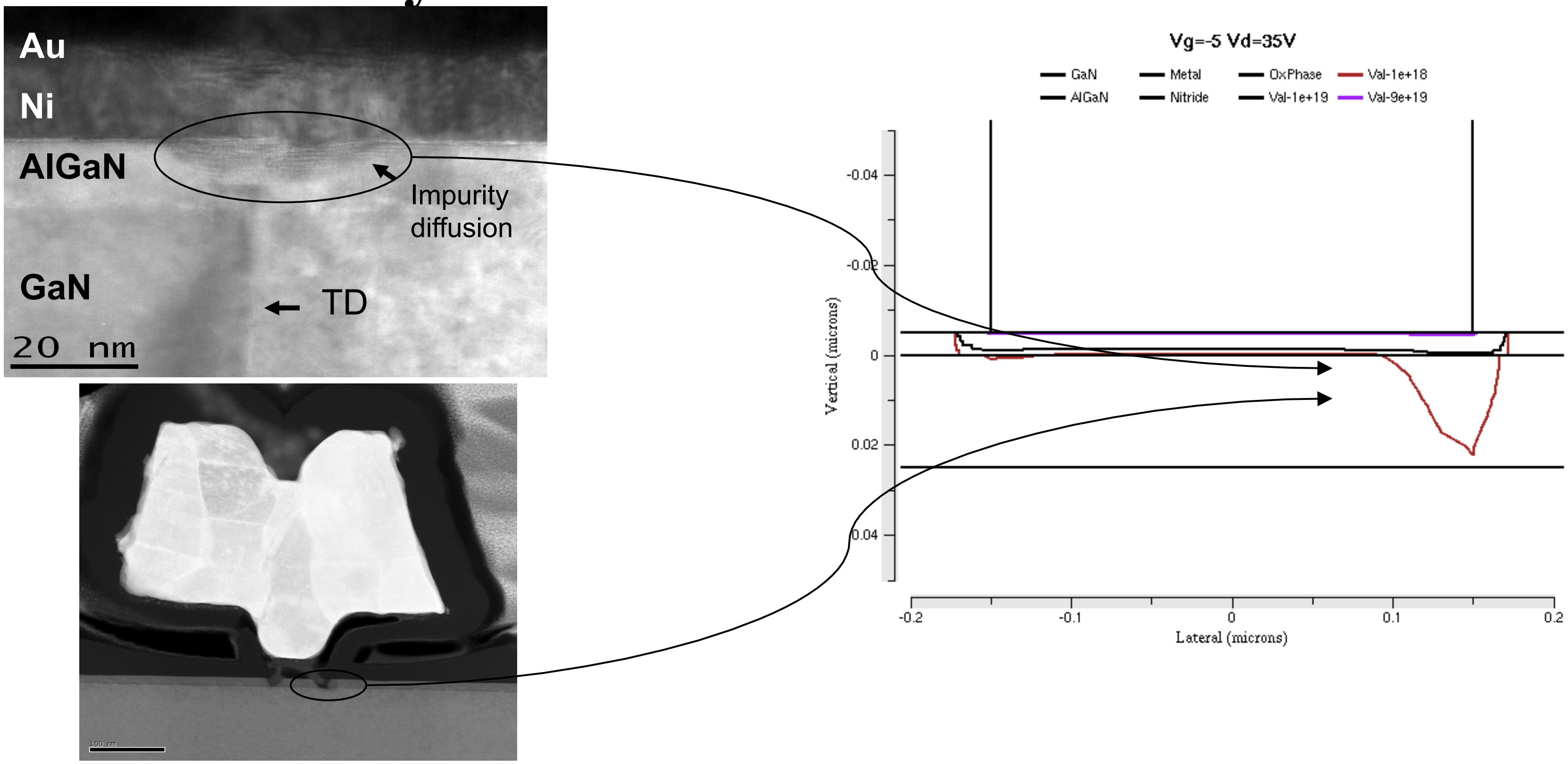
Strain↕dir & Impurity diffusion
Vg=-5V Vd=35V





Max calculated strain in AlGaN layer (↕ dir) =-1e-3 (**compressive**)
Max calculated strain in AlGaN layer (↔ dir)=4.8e-4 (**tensile**)

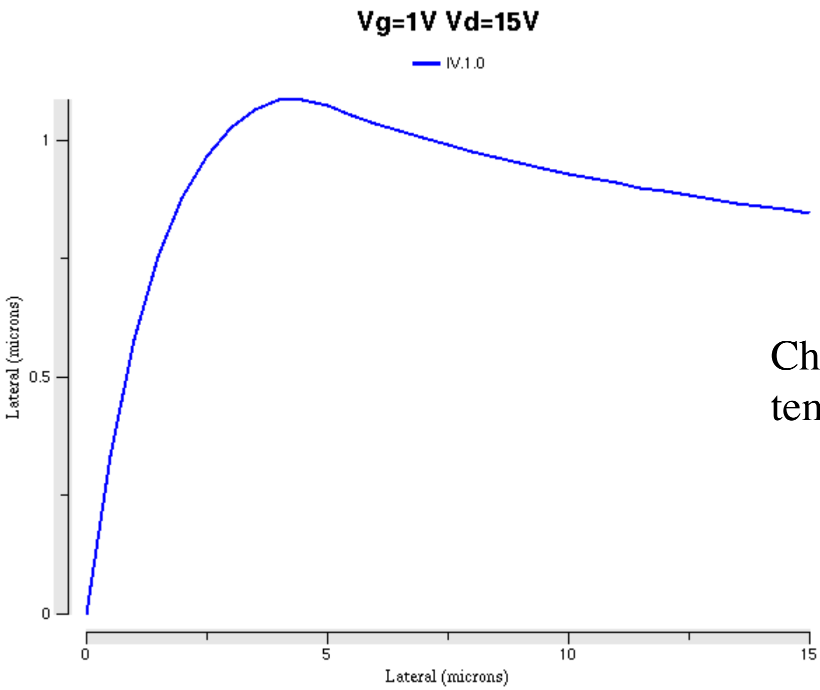
Physical data vs Simulation

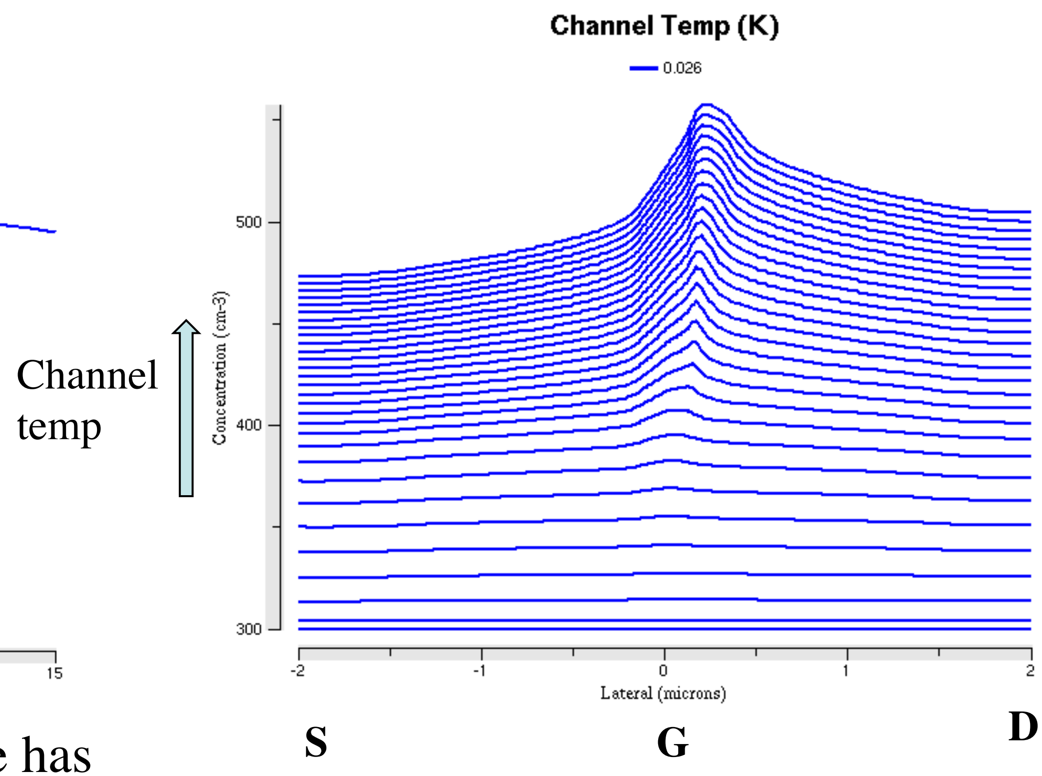


- Simulated Ids MAX drop ~ 40% for similar physical degradation.
- Critical Vd in simulation still does not match physical data.
  (15V vs ~38V)

5] Joh, J, del Alamo J. Electron Device Letters, IEEE JNL Volume 29, No 4. 2008 pp:287– 289

Implemented: Effect of Temperature on Ids





- For On/High Power state, device has appreciable self heating ~550K
- $\frac{dT}{dt} = k * \nabla^2 T * \mu * n * \frac{dQfn}{dx}$

References

- 1] Park S.Y, Kim, M.J et al Microelectronics Reliability 49 2009 pp:478– 483
- 2] Kuball, M et al Microelectronics Reliability 51 2011 pp:195– 200
- 3] Tapajna M, Mishra U.K., Kuball M. Applied Phys. Lett. Vol 97, No 023503, 2010
- 4] Ren, F et al. JVST B 5 Microelectronics and Nanometer structures Apr 2011
- 5] Joh, J, del Alamo J. Electron Device Letters, IEEE JNL Volume 29, No 4. 2008 pp: 287– 289
- 6] Nicolet, M. A Thin Solid Films, Volume 52, 1978 pp:415– 443
- 7] Holzworth, M. R, Rudawski, N.G, Pearton, S.J, Ren, F Applied Phys. Lett. Vol 98, No 122103, 2011

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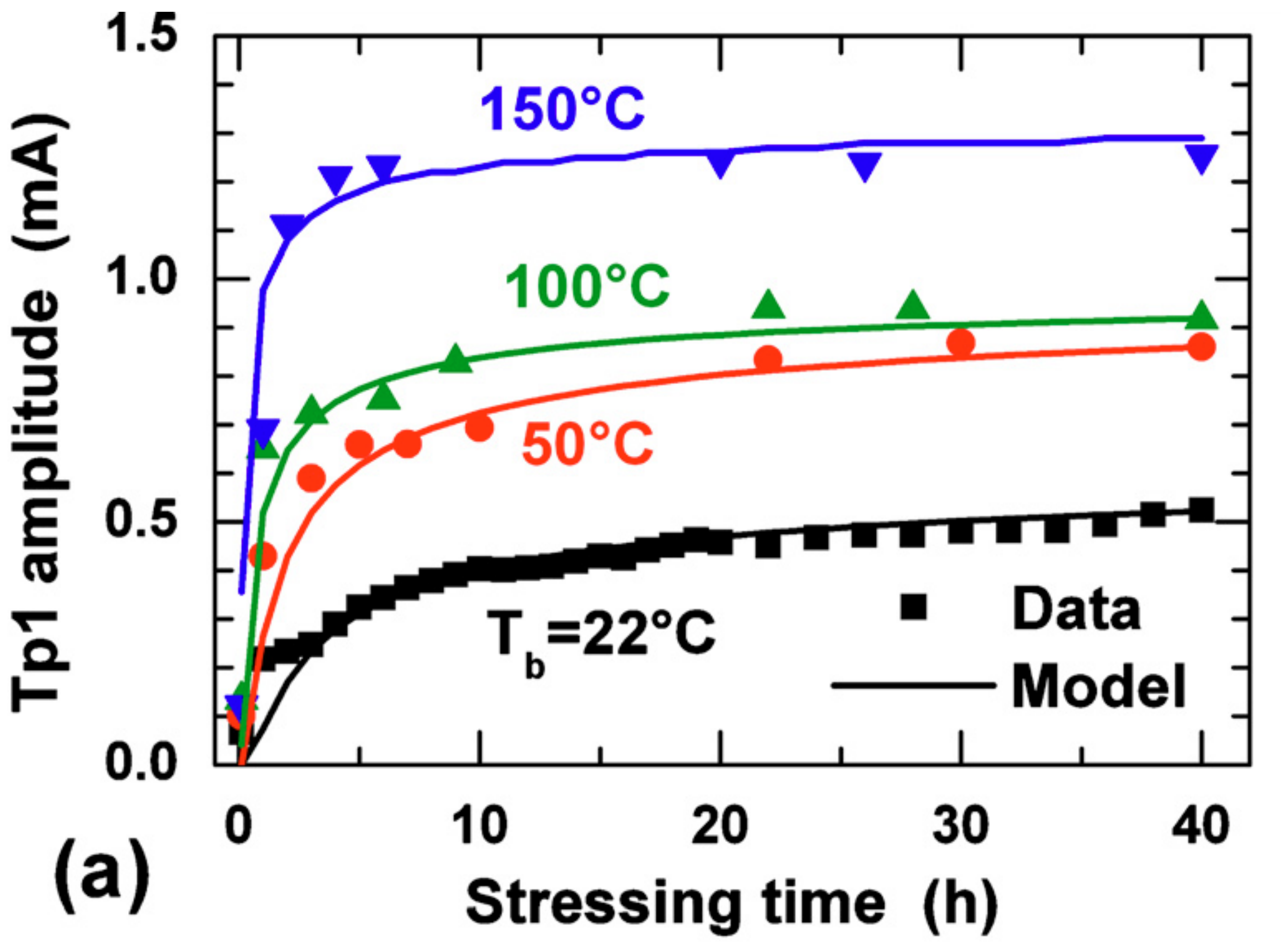
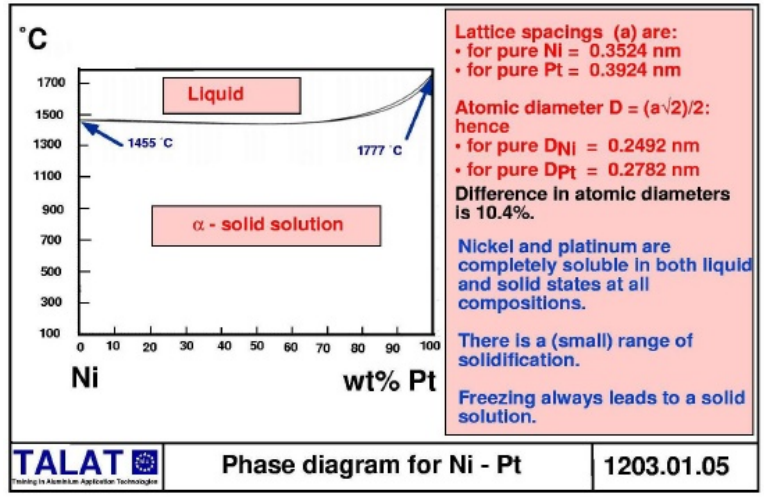


Ni/Pt Phase diagram

- Full range of Ni/Pt alloy forms 1 phase below 1450°C



Ni/Au Phase diagram

- large range of Ni/Au alloy forms 2 phases below 700°C